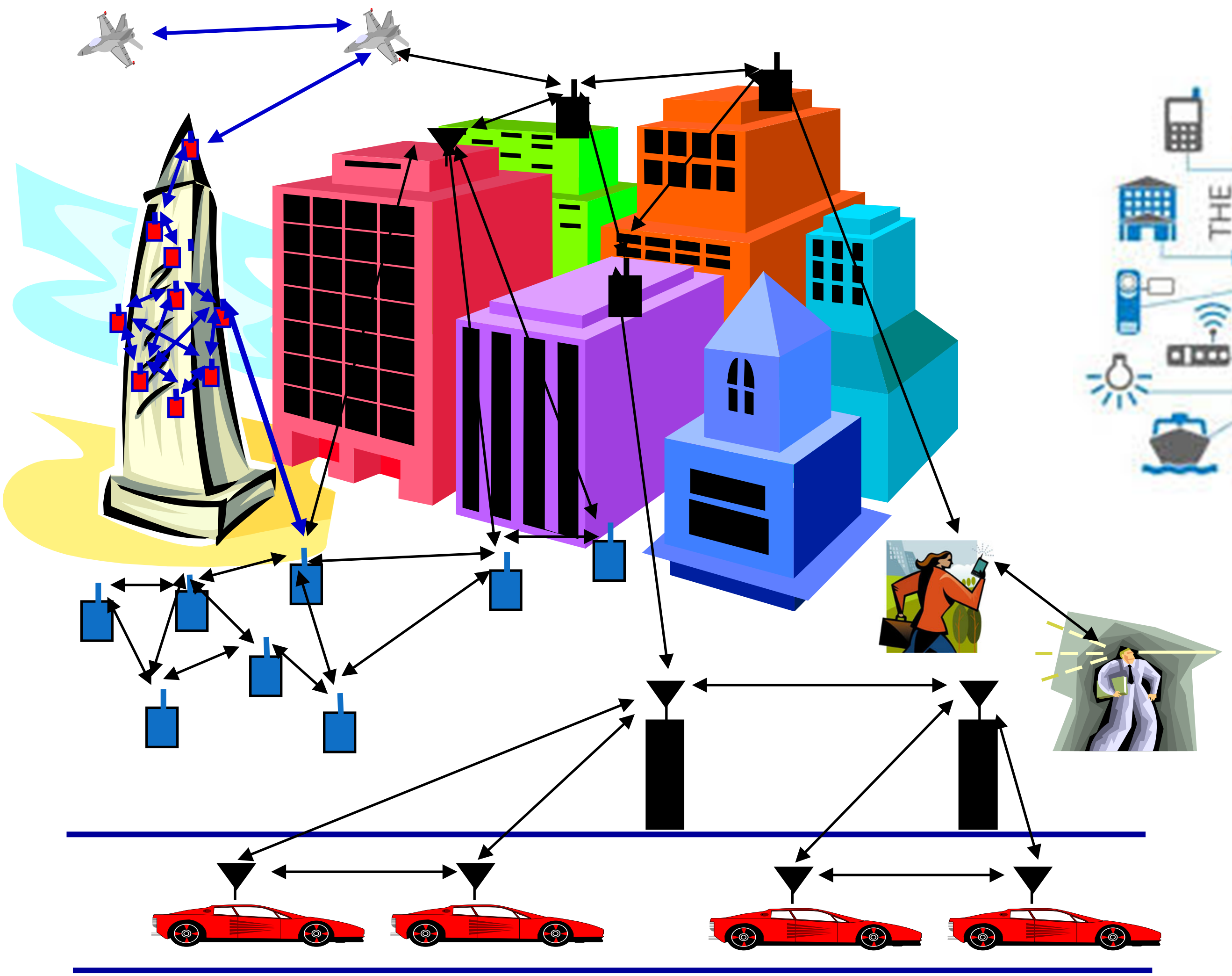
EE 359: Wireless Communications

Advanced Topics in Wireless

Dec. 7, 2017

Future Wireless Networks

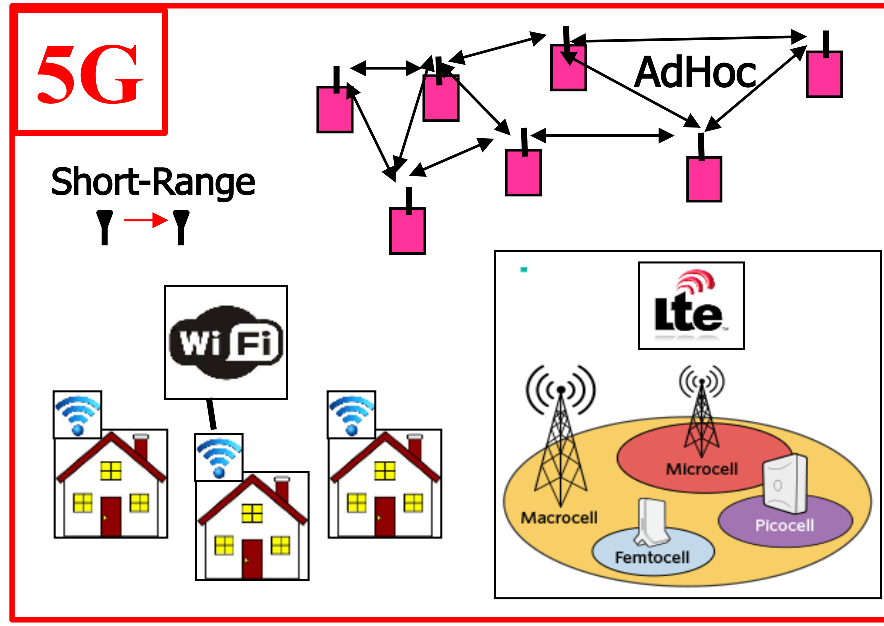
Ubiquitous Communication Among People and Devices



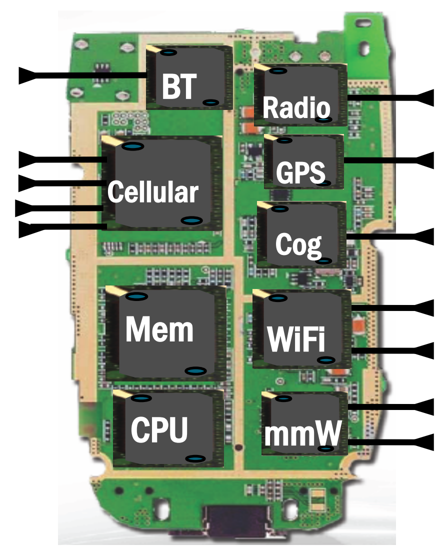
Next-Gen Cellular/WiFi
Smart Homes/Spaces
Autonomous Cars
Smart Cities
Body-Area Networks
Internet of Things
All this and more …

Challenges

- Network Challenges
  - High performance
  - Extreme energy efficiency
  - Scarce/bifurcated spectrum
  - Heterogeneous networks
  - Reliability and coverage
  - Seamless internetwork handoff



- Device/SoC Challenges
  - Performance
  - Complexity
  - Size, Power, Cost
  - High frequencies/mmWave
  - Multiple Antennas
  - Multiradio Integration
  - Coexistance

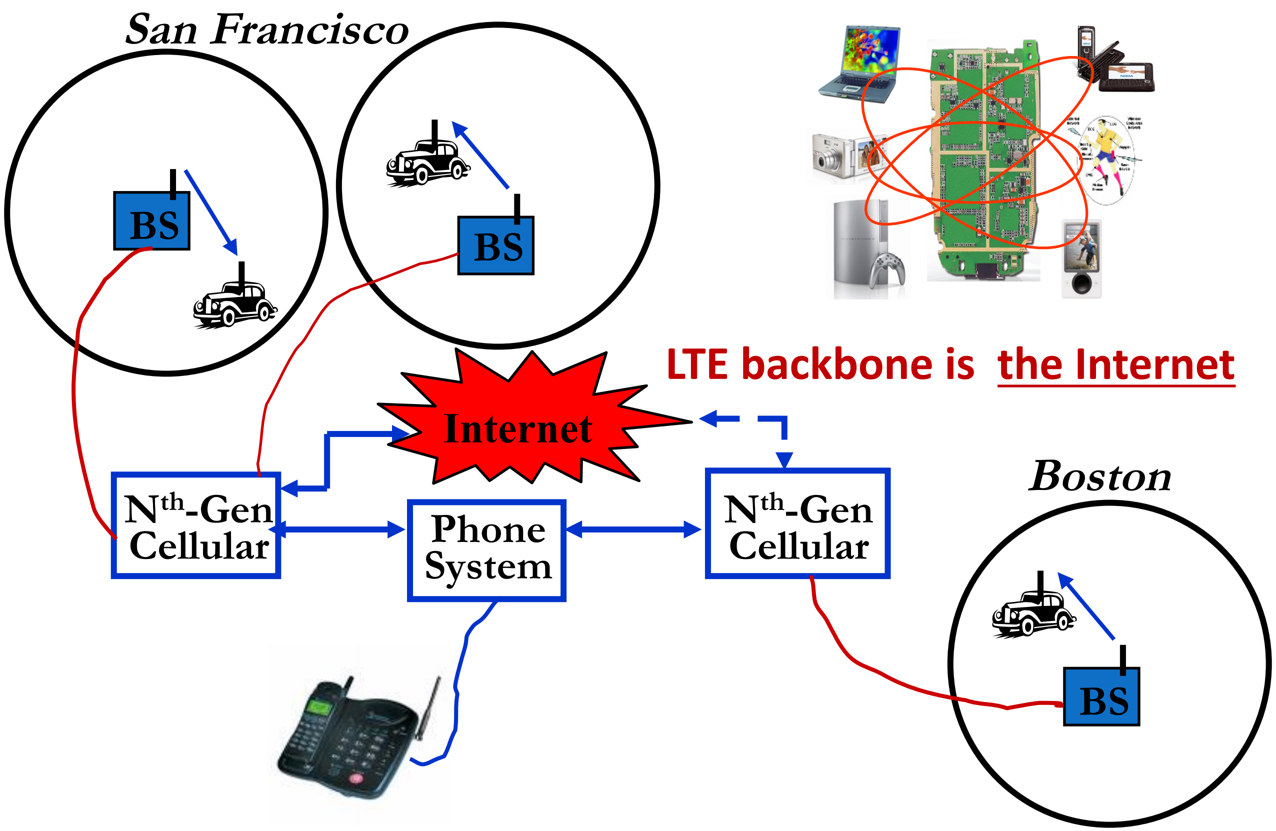


Emerging Systems

- New cellular system architectures
- mmWave/massive MIMO communications
- Software-defined network architectures
- Ad hoc/mesh wireless networks
- Cognitive radio networks
- Wireless sensor networks
- Energy-constrained radios
- Distributed control networks
- Chemical Communications
- Applications of Communications in Health, Bio-medicine, and Neuroscience

Future Cell Phones

Burden for this performance is on the backbone network

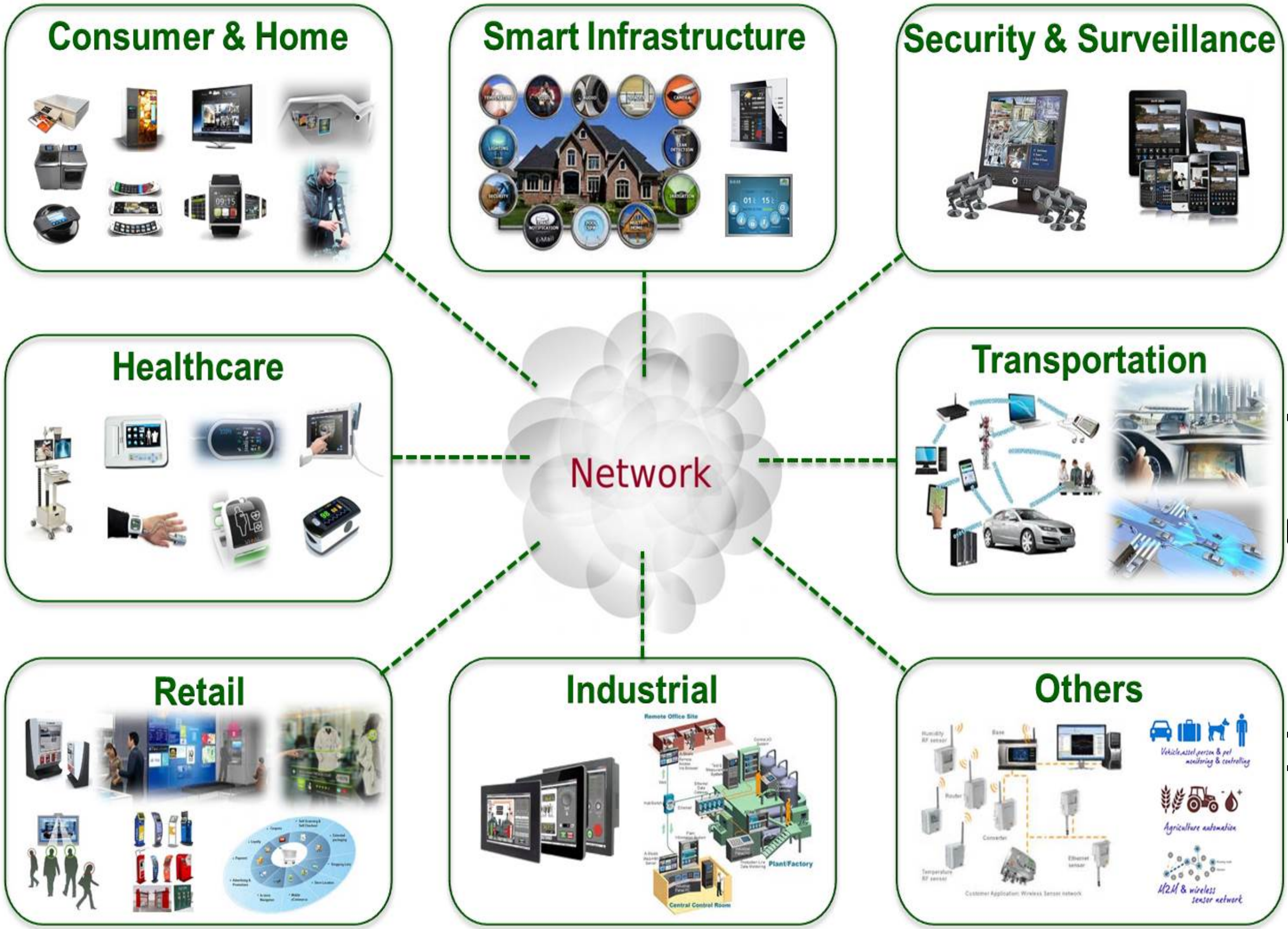


Much better performance and reliability than today

- Gbps rates, low latency/energy , 99.999% coverage

What is the Internet of Things:

- Er co
- In ics, ca ces,...
- Va d



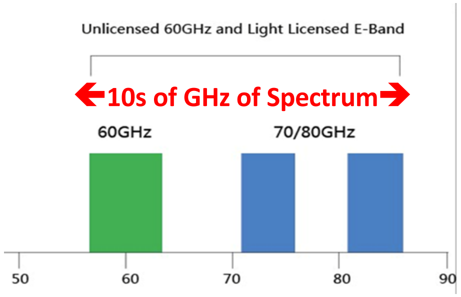
Different requirements than smartphones: low rates/energy consumption

The Licensed Airwaves are "Full"

Source: FCC

Also have Wifi

And mmWave

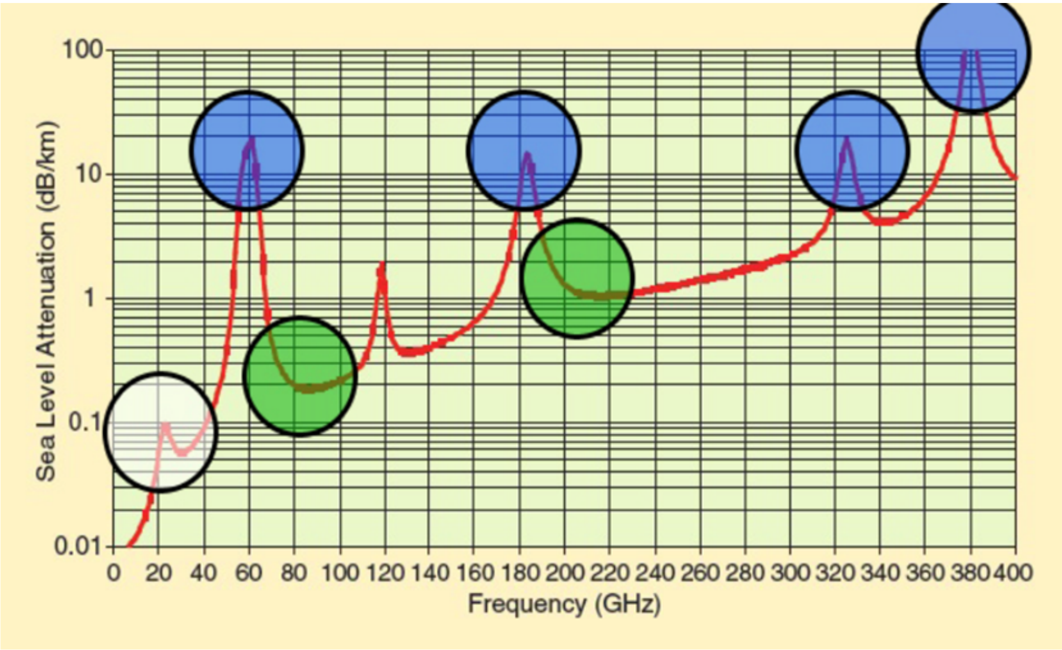


Enablers for increasing wireless data rates

- More spectrum (mmWave)
- (Massive) MIMO
- Innovations in cellular system design
- Software-defined wireless networking

mmW as the next spectral frontier

- Large bandwidth allocations, far beyond the 20MHz of 4G
- Rain and atmosphere absorption not a big issue in small cells



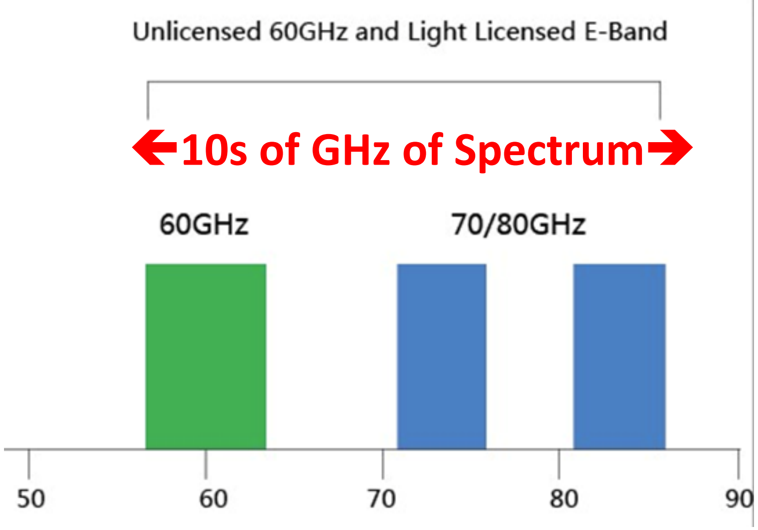
  - Not that high at some frequencies; can be overcome with MIMO
- Need cost-effective mmWave CMOS; products now available
- Challenges: Range, cost, channel estimation, large arrays

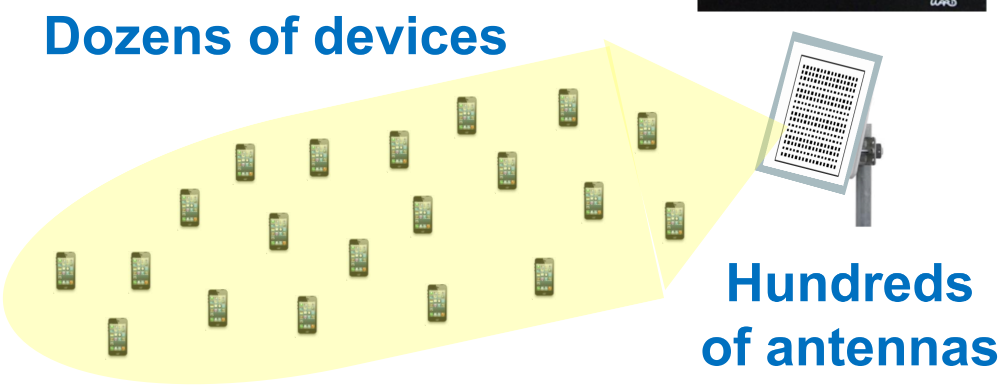
What is Massive MIMO?

- A very large antenna array at each base station
  - An order of magnitude more antenna elements than in conventional systems
- A large number of users are served simultaneously
- An excess of base station (BS) antennas
- Essentially multiuser MIMO with lots of base station antennas

T. L. Marzetta, “Noncooperative cellular wireless with unlimited numbers of base station antennas,” IEEE Trans. Wireless Commun., vol. 9, no. 11, pp. 3590–3600, Nov. 2010.

mmWave Massive MIMO

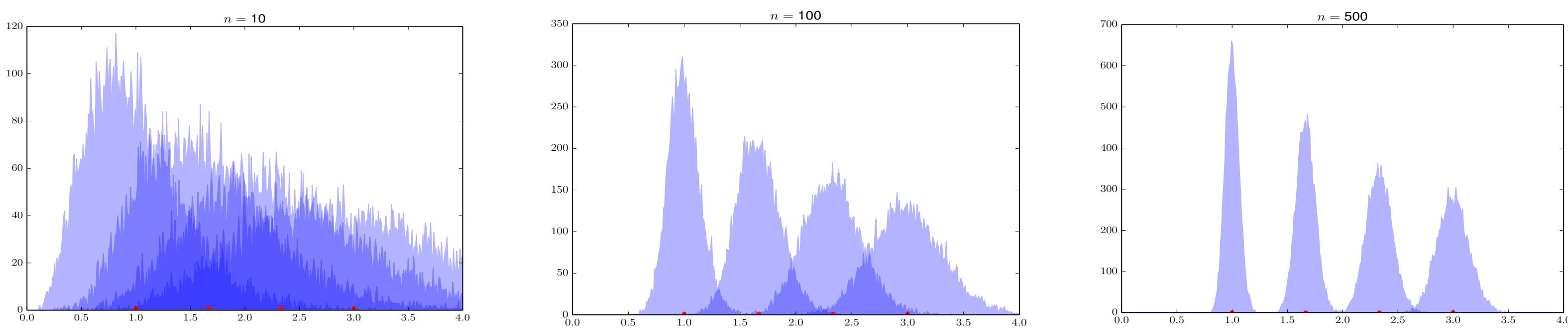




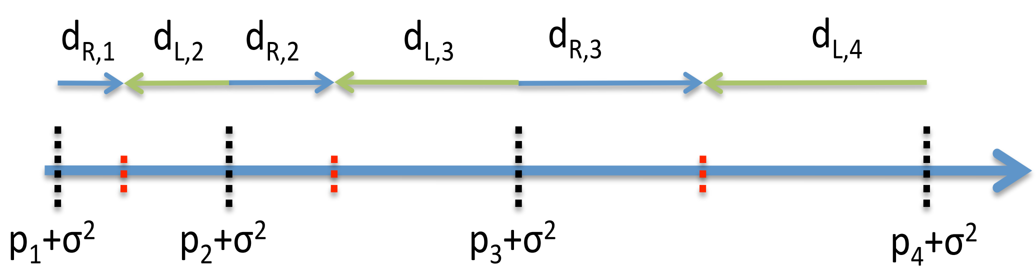
- mmWaves have large attenuation and path loss
- For asymptotically large arrays with channel state information, no attenuation, fading, interference or noise
- mmWave antennas are small: perfect for massive MIMO
- Bottlenecks: channel estimation and system complexity
- Non-coherent design holds significant promise

Non-coherent massive MIMO

- Propose simple energy-based modulation
- No capacity loss for large arrays: $\lim_{n\to\infty} C_{nocsi} = \lim_{n\to\infty} C_{csi}$
  - Holds for single/multiple users (1 TX antenna, n RX antennas)

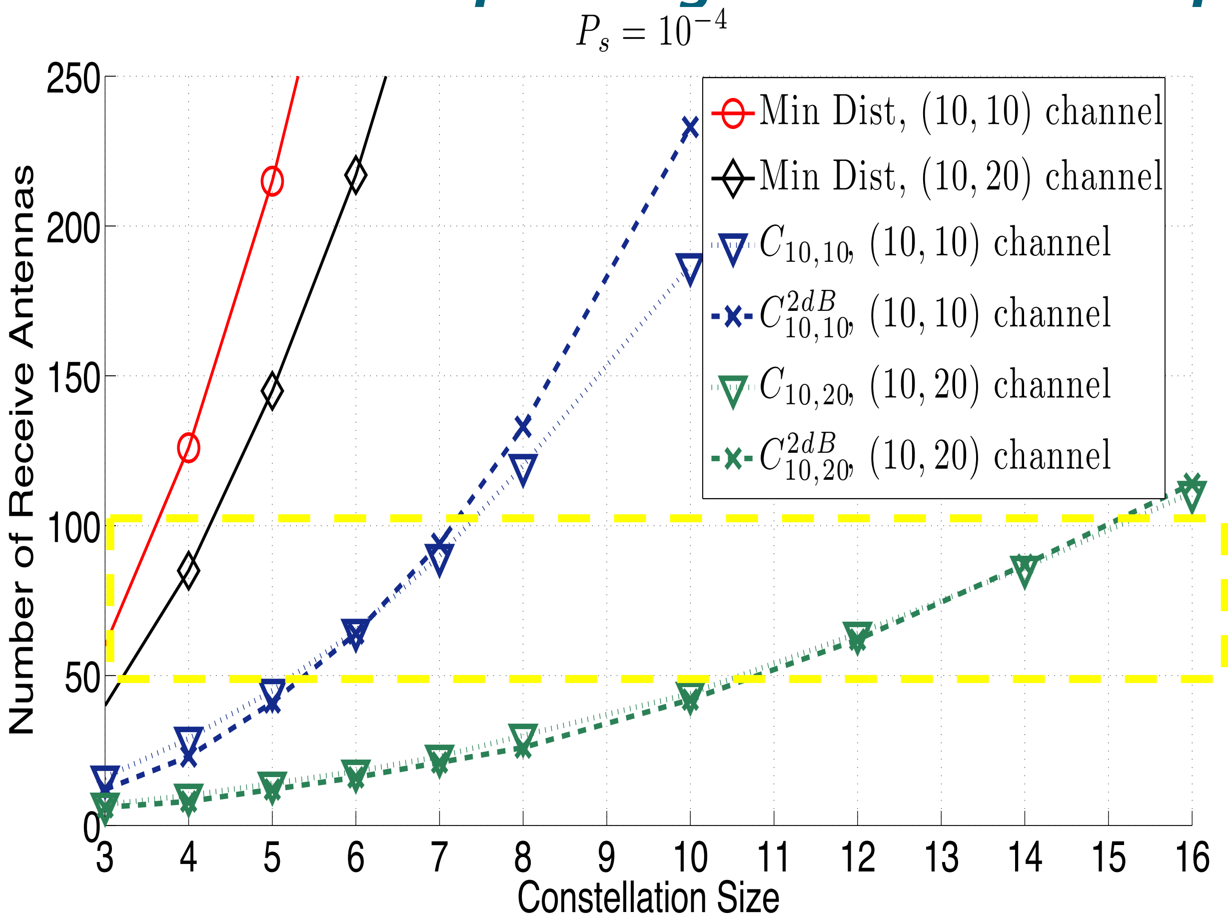


- Constellation optimization: unequal spacing



Need 50-100 antennas for an SER of 10^{-4}

Depending on data rate requirements

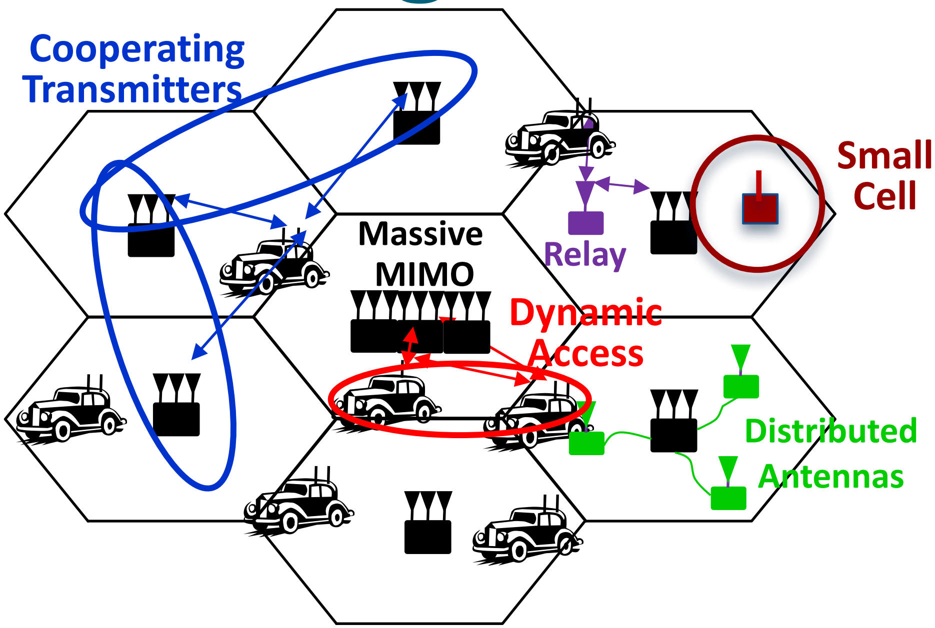


Minimum Distance Design criterion: Significantly worse performance than the new designs.

Design robust to channel uncertainty

Noncoherent communication demonstrates promising performance with reasonably-sized arrays

Rethinking Cellular System Design



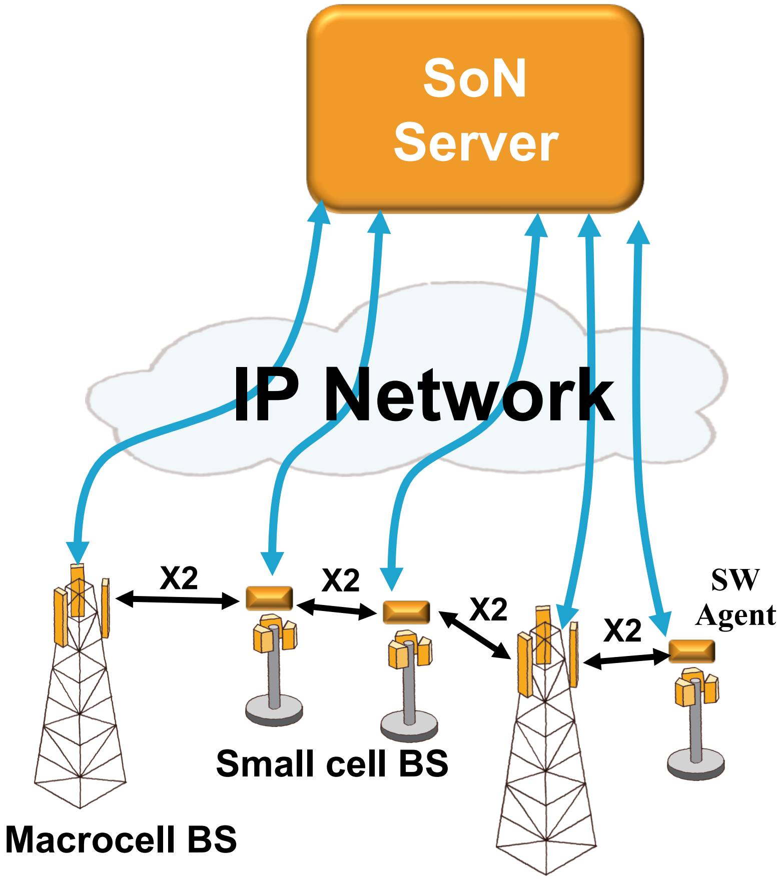
How should cellular systems be designed?

Will gains be big or incremental; in capacity, coverage or energy?

- Traditional cellular design assumes system is “interference-limited”
- No longer the case with recent technology advances:
  - MIMO, multiuser detection, cooperating BSs (CoMP) and relays
- Raises interesting questions such as “what is a cell?”
- Energy efficiency via distributed antennas, small cells, MIMO, and relays
- Dynamic self-organization (SoN) needed for deployment and optimization

Small cells are the solution to increasing cellular system capacity

In theory, provide exponential capacity gain



- Future cellular networks will be hierarchical
  - Large cells for coverage
  - Small cells for capacity and power efficiency
  - Small cells require self-optimization in the cloud
- Small Cell Challenges
  - SoN algorithmic complexity
  - Distributed vs centralized control
  - Backhaul and site acquisition

WiFi is the small cell of today

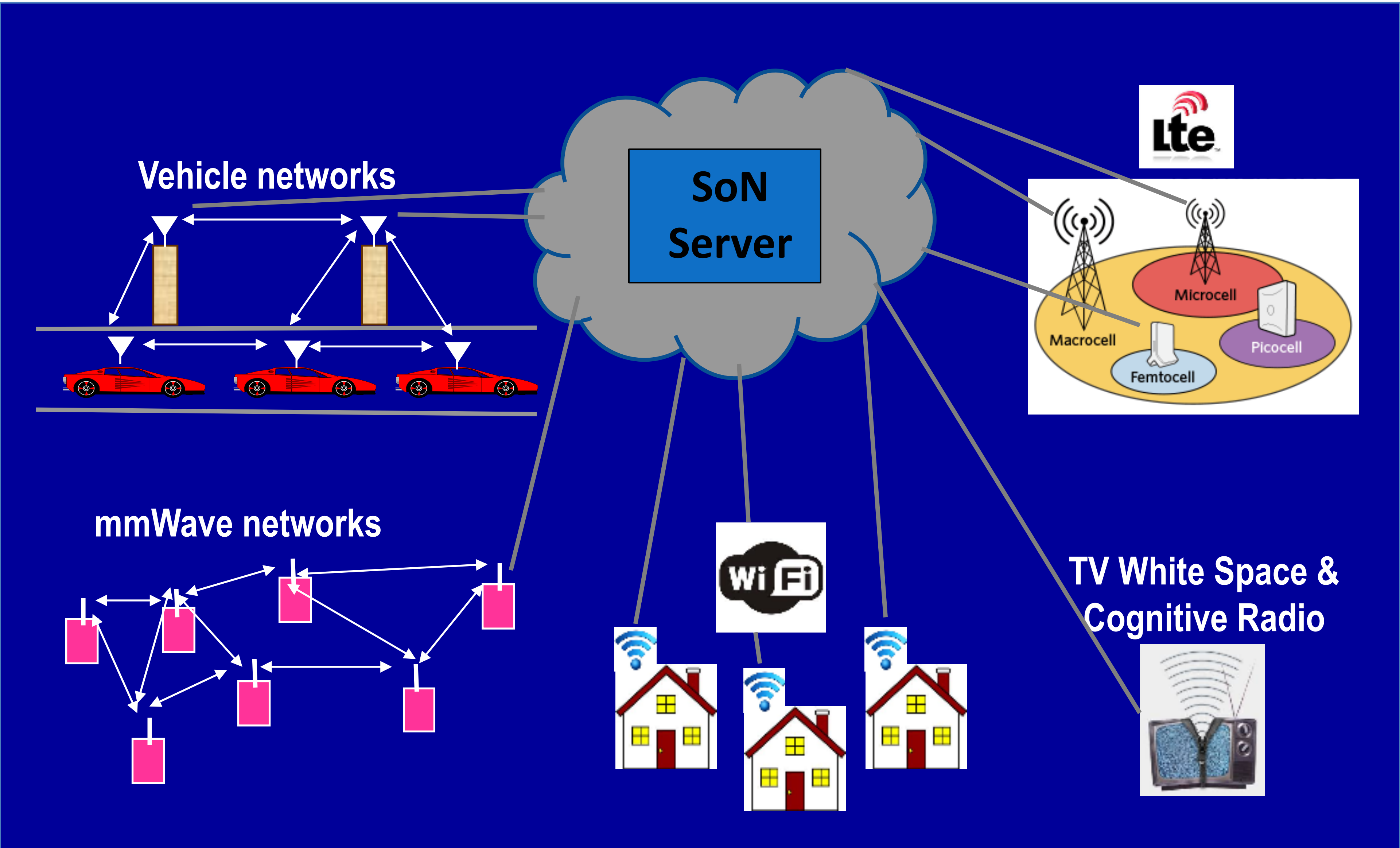
Primary access mode in residences, offices, and wherever you can get a WiFi signal

Lots of spectrum, excellent PHY design

The Big Problem with WiFi

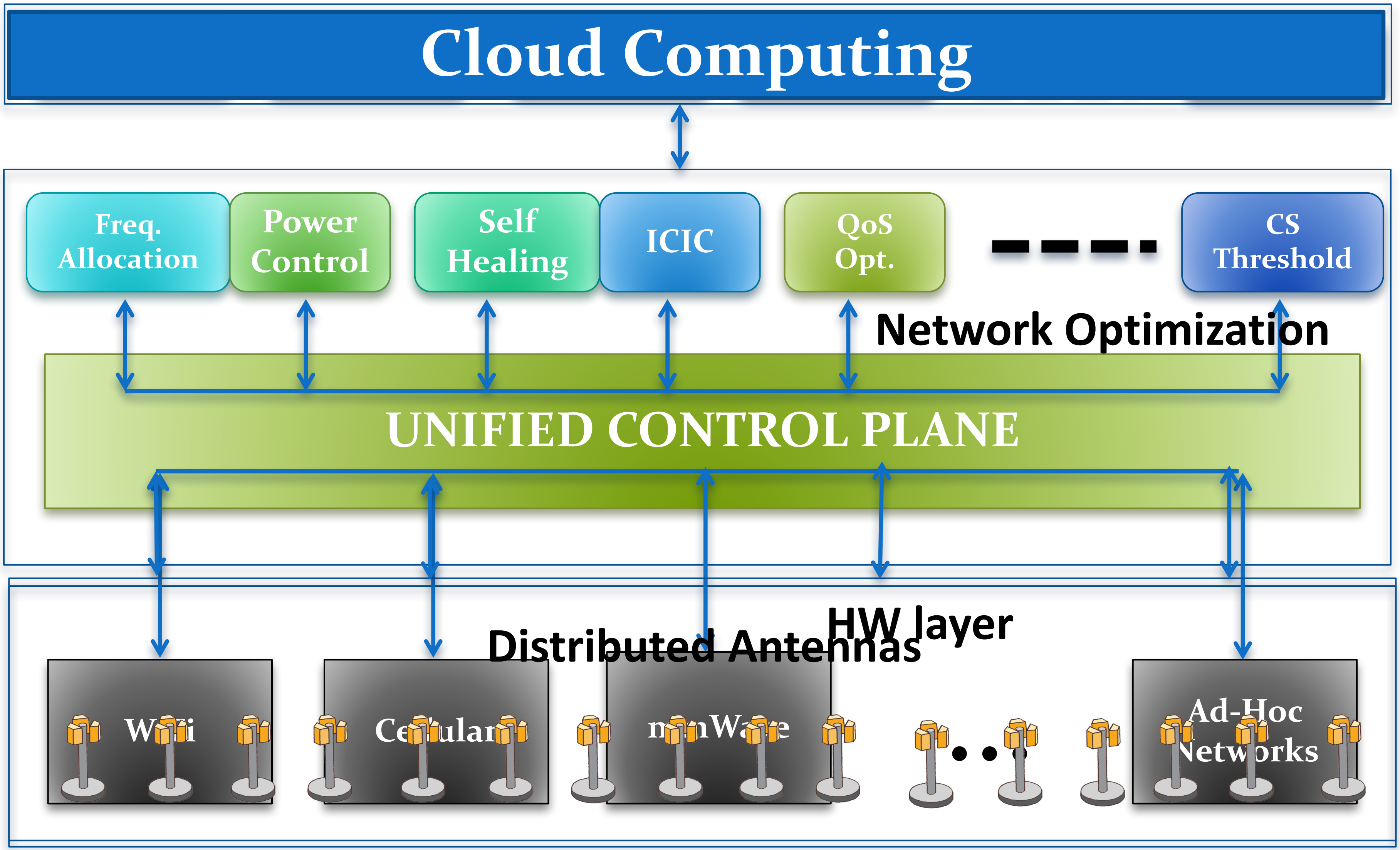
- The WiFi standard lacks good mechanisms to mitigate interference in dense AP deployments
  - Static channel assignment, power levels, and carrier sense thresholds
  - In such deployments WiFi systems exhibit poor spectrum reuse and significant contention among APs and clients
  - Result is low throughput and a poor user experience

Why not use SoN for all wireless networks?



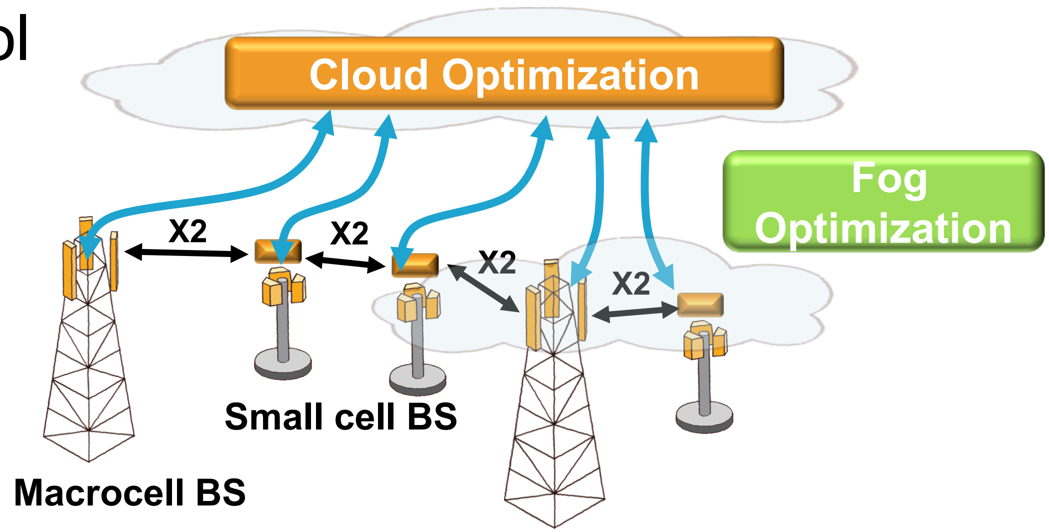
Software-Defined Network Architecture

(generalization of NFV, SDN, cloud-RAN, and distributed cloud)



SDWN Challenges

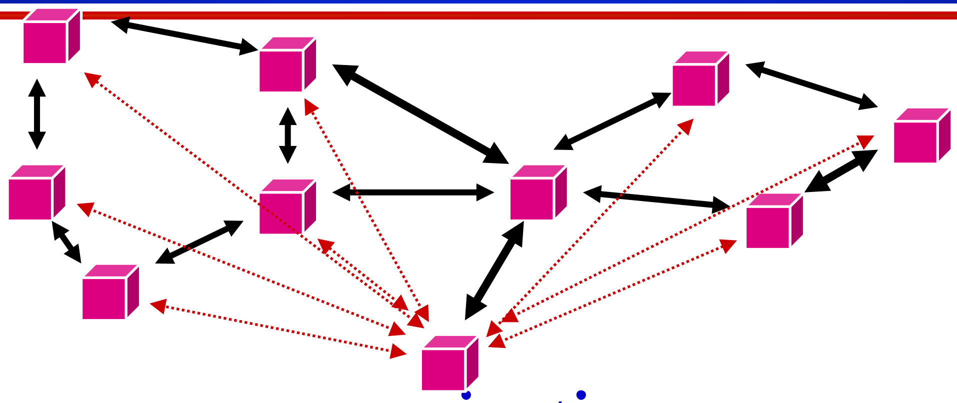
- Algorithmic complexity
  - Frequency allocation alone is NP hard
  - Also have MIMO, power control, CST, hierarchical networks: *NP-really-hard*
  - Advanced optimization tools needed, including a combination of centralized (cloud) distributed, and locally centralized (fog) control
- Hardware Interfaces
- Seamless handoff
- Resource pooling



New PHY and MAC Techniques

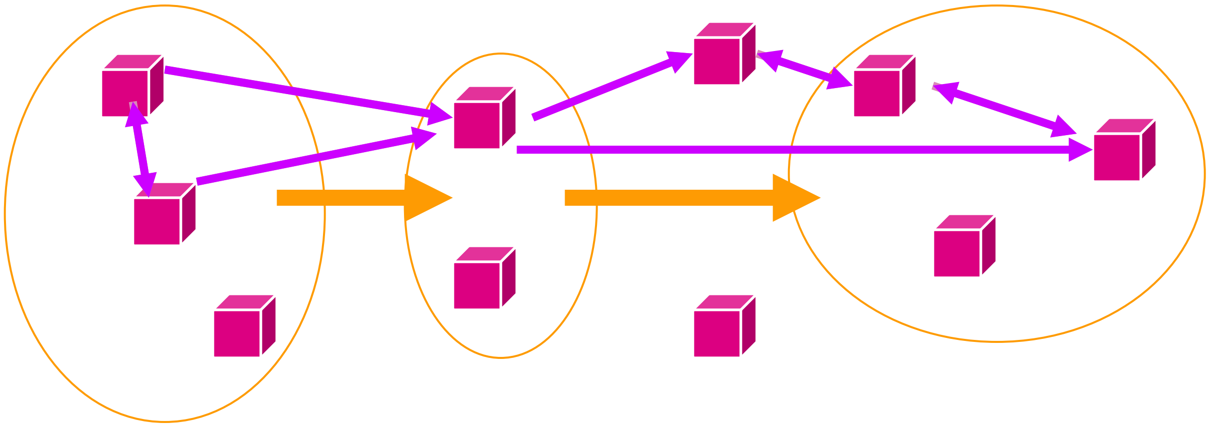
- New Waveforms
  - Robust to rapidly changing channels (OTFS)
  - More flexible and efficient subcarrier allocation (variants of OFDM)
- Coding
  - Incremental research (polar vs. LDPC), no new breakthroughs
- Access
  - Efficient access for low-rate IoT Devices (sparse code MAC, GFDM, OTFS, variants of OFDMA)
  - Access/interference mitigation for unlicensed LTE

Ad-Hoc Networks



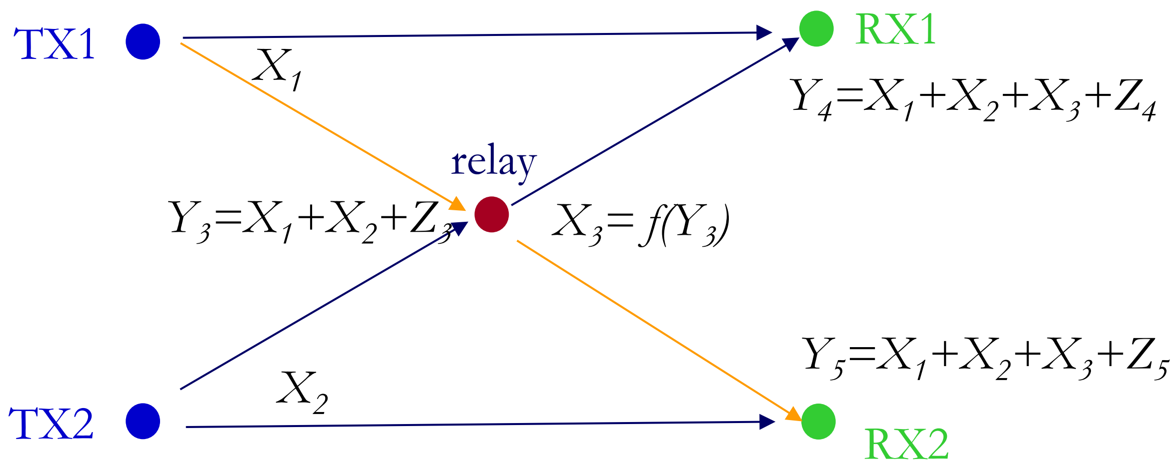
- Peer-to-peer communications
  - No backbone infrastructure or centralized control
- Routing can be multihop.
- Topology is dynamic.
- Fully connected with different link SINRs
- Open questions
  - Fundamental capacity region
  - Resource allocation (power, rate, spectrum, etc.)
  - Routing

Cooperation in Wireless Networks



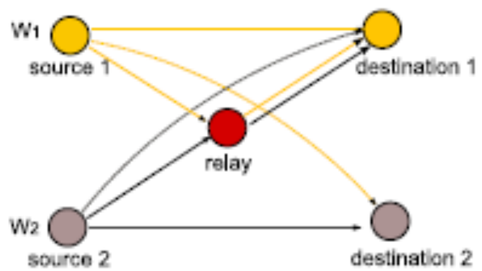
- Many possible cooperation strategies:
  - Virtual MIMO, relaying (DF, CF, AF), one-shot/iterative conferencing, and network coding
  - Nodes can use orthogonal or non-orthogonal channels.
  - Many practice and theoretical challenges
  - New full duplex relays can be exploited

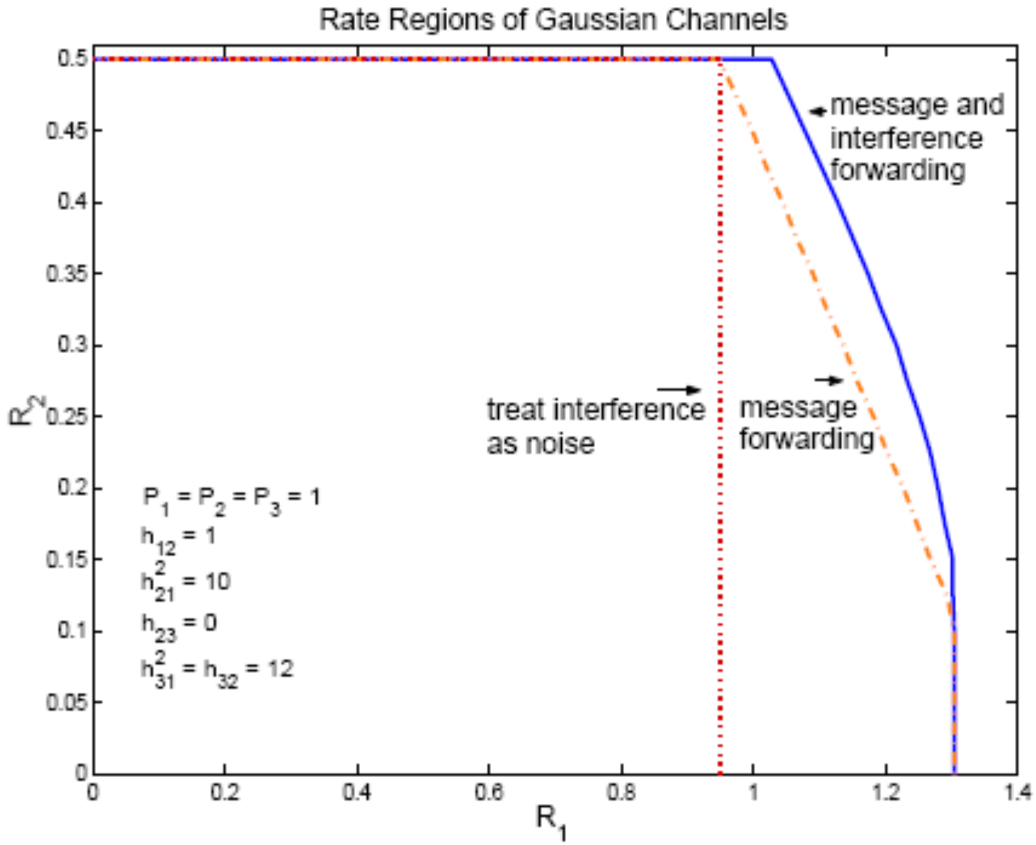
General Relay Strategies



- Can forward message and/or interference
  - **Relay can forward all or part of the messages**
    - **Much room for innovation**
  - **Relay can forward interference**
    - **To help subtract it out**

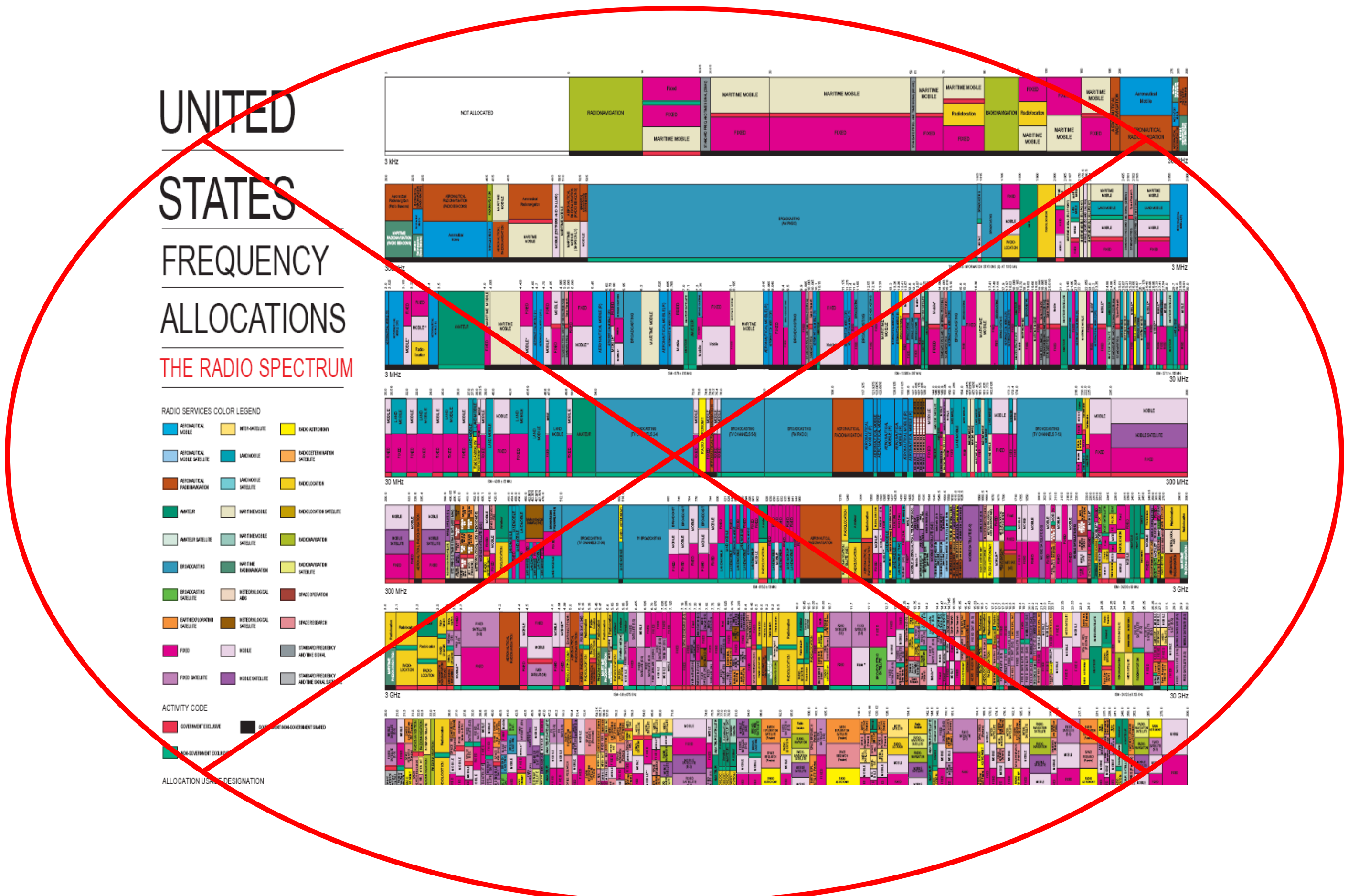
Beneficial to forward both interference and message



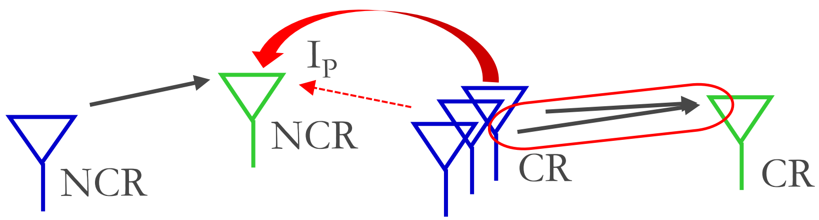


- For large powers, this strategy approaches capacity

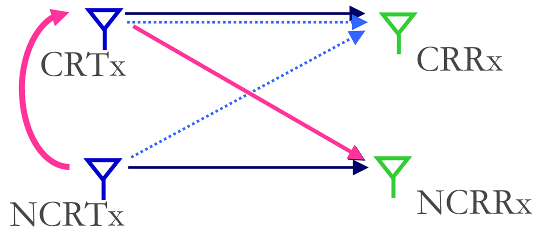
Spectrum innovations beyond licensed/unlicensed paradigms



Cognitive Radios



MIMO Cognitive Underlay

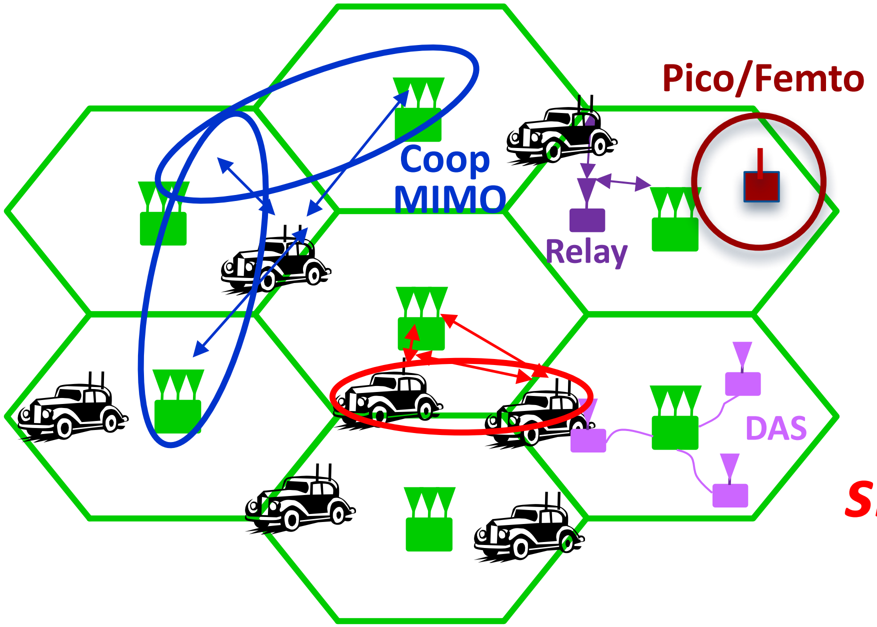


Cognitive Overlay

- **Cognitive radios support new users in existing crowded spectrum <u>without degrading licensed users</u>**
  - **Utilize advanced communication and DSP techniques**
  - **Coupled with novel spectrum allocation policies**

- **Multiple paradigms**
  - **(MIMO) Underlay (interference below a threshold)**
  - **Interweave finds/uses unused time/freq/space slots**
  - **Overlay (overhears/relays primary message while cancelling interference it causes to cognitive receiver)**

"Green" Wireless Networks



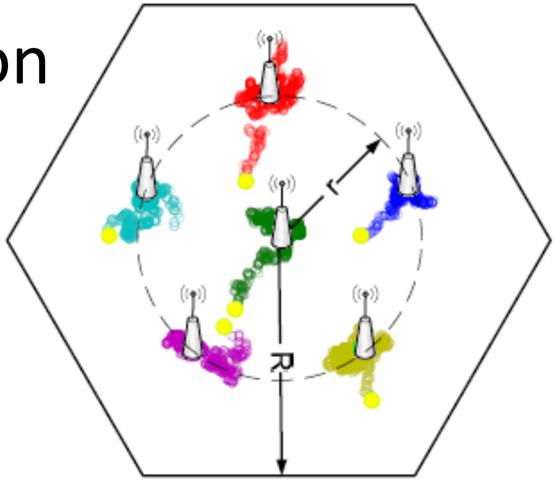
How should wireless systems be redesigned for minimum energy?

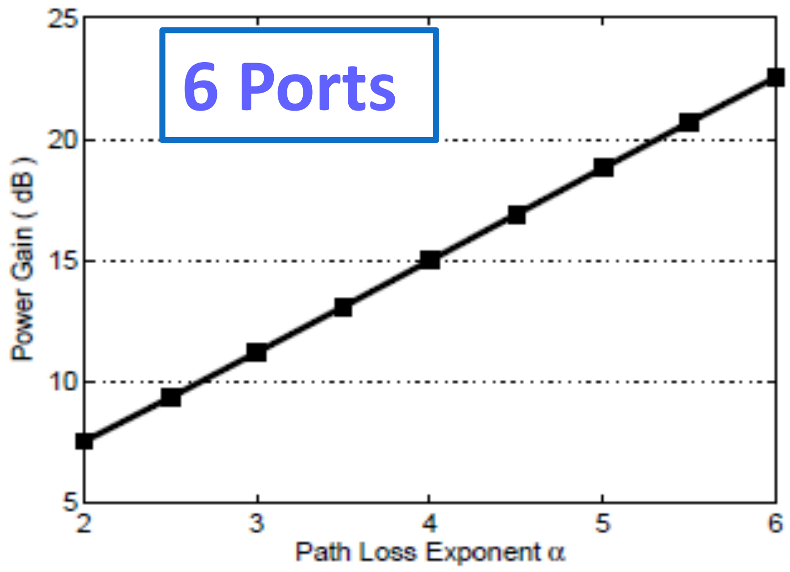
Research indicates that significant savings is possible

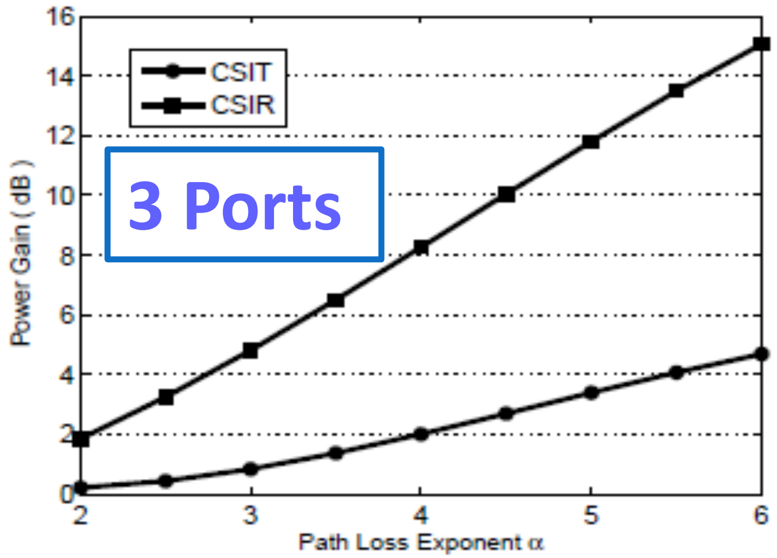
- Drastic energy reduction needed (especially for IoT)
  - New Infrastuctures: Cell Size, BS/AP placement, Distributed Antennas (DAS), Massive MIMO, Relays
  - New Protocols: Coop MIMO, RRM, Sleeping, Relaying
  - Low-Power (Green) Radios: Radio Architectures, Modulation, Coding, Massive MIMO

DAS to minimize energy

- Optimize distributed BS antenna location
- Primal/dual optimization framework
- Convex; standard solutions apply
- For 4+ ports, one moves to the center
- **Up to 23 dB power gain in downlink**
  - **Gain higher when CSIT not available**



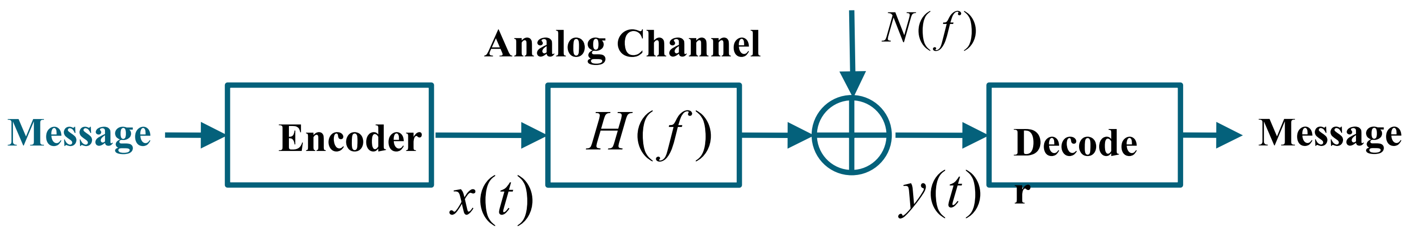




Energy-Constrained Radios

- Transmit energy minimized by sending bits very slowly
  - Leads to increased circuit energy consumption
- Short-range networks must consider both transmit and processing/circuit energy.
  - Sophisticated encoding/decoding not always energy-efficient.
  - MIMO techniques not necessarily energy-efficient
  - Long transmission times not necessarily optimal
  - Multihop routing not necessarily optimal
- Sub-Nyquist Sampling

Sub-Nyquist Sampled Channels



C. Shannon

Wideband systems may preclude Nyquist-rate sampling!

H. Nyquist

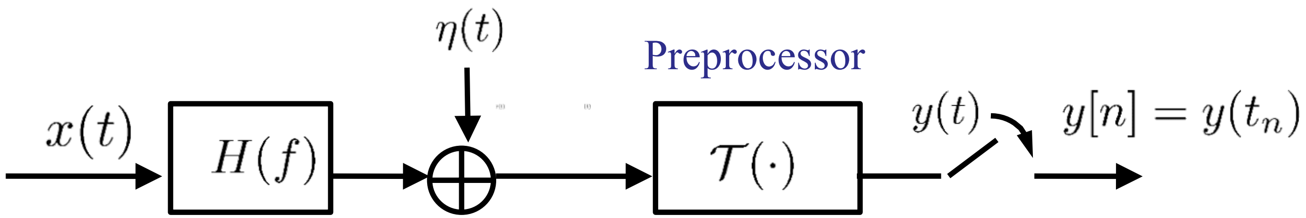
Sub-Nyquist sampling well explored in signal processing

- ***Landau-rate sampling, compressed sensing, etc.***
- ***Performance metric: MSE***

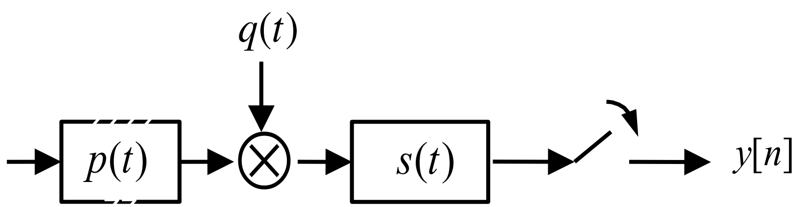
We ask: what is the capacity-achieving sub-Nyquist sampler and communication design

Capacity and Sub-Nyquist Sampling

- Consider linear time-invariant sub-sampled channels



- Theorem: Capacity-achieving sampler



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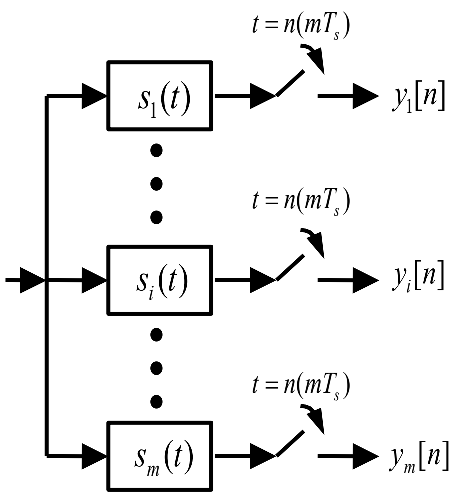
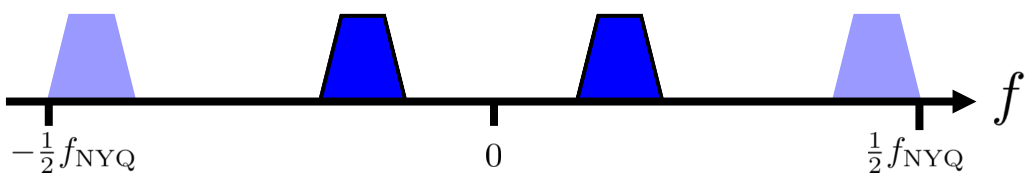


Optimal filters suppress aliasing

- Sub-Nyquist sampling is optimal for some channels!

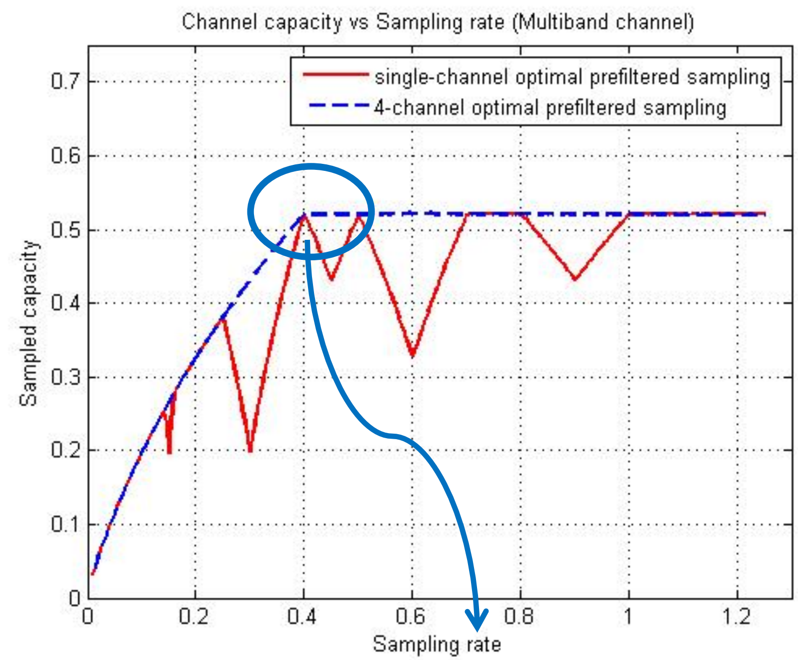
Example: Multiband Channel

- **Consider a "sparse" channel, and an optimally designed 4-branch filter bank sampler**



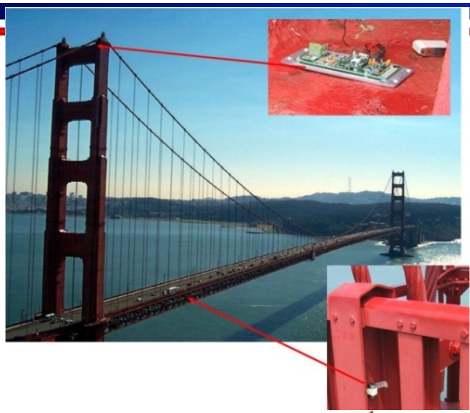
- **Outperforms single-branch sampling.**

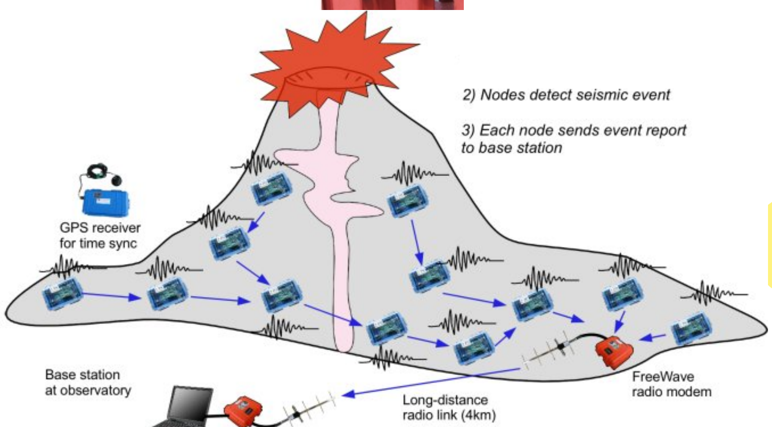
- **Achieves full-capacity above *Landau Rate***

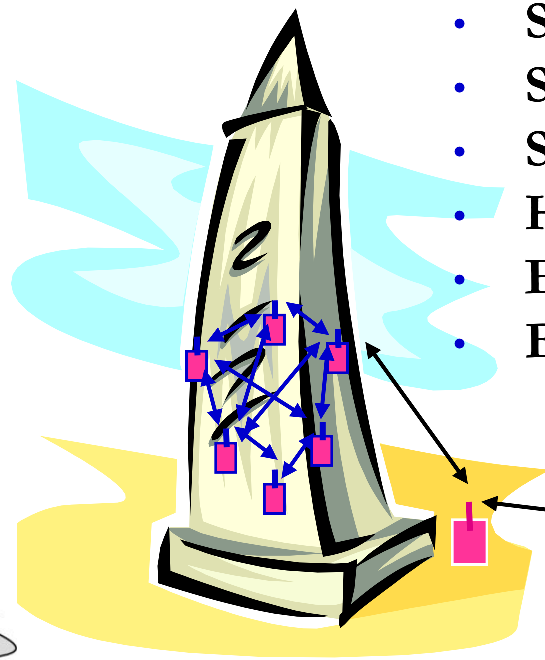


Landau Rate: sum of total bandwidths

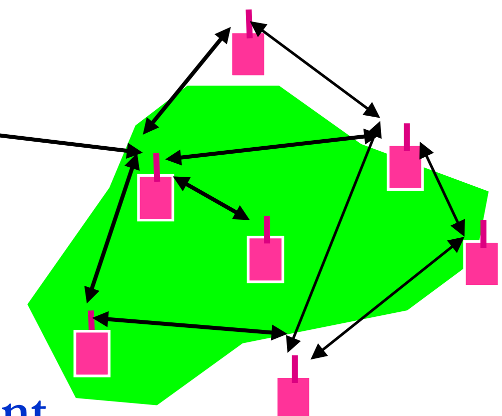
Wireless Sensor Networks
Data Collection and Distributed Control







- Smart homes/buildings
- Smart structures
- Search and rescue
- Homeland security
- Event detection
- Battlefield surveillance

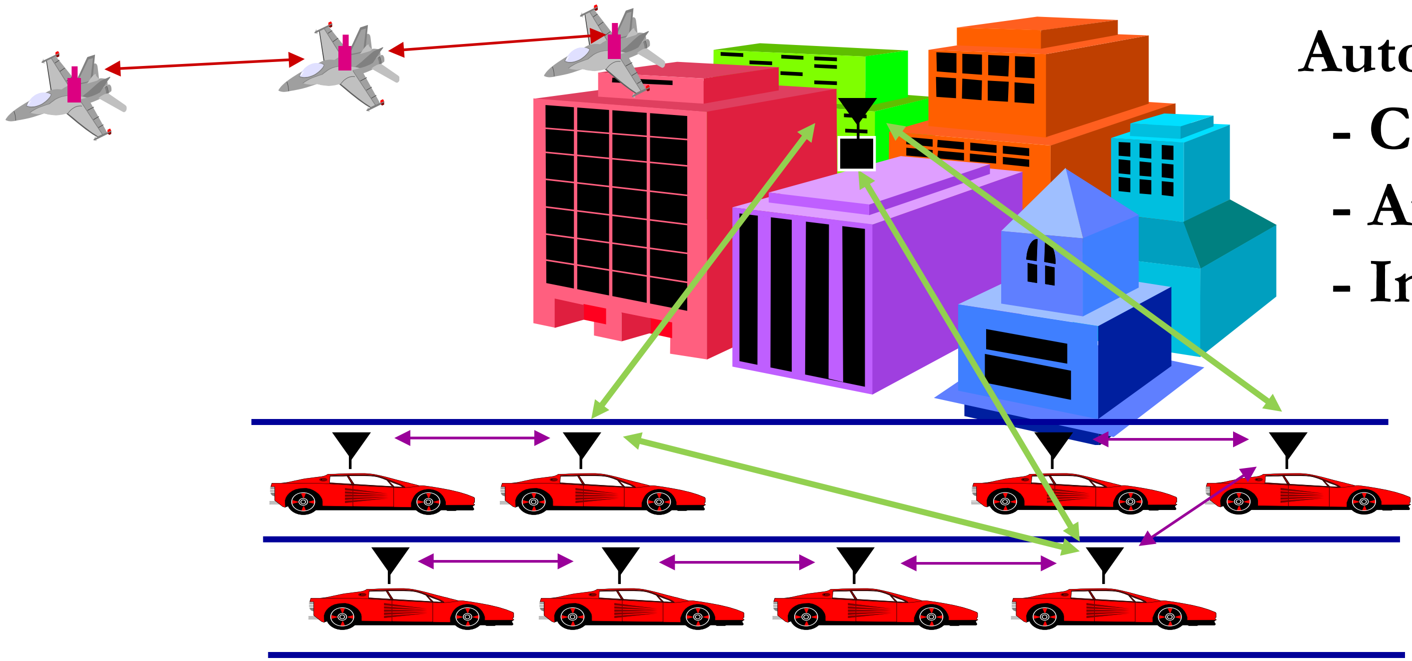


- Energy (transmit and processing) is the driving constraint
- Data flows to centralized location (joint compression)
- Low per-node rates but tens to thousands of nodes
- Intelligence is in the network rather than in the devices

Where should energy come from?

- Batteries and traditional charging mechanisms
  - Well-understood devices and systems
- Wireless-power transfer
  - Poorly understood, especially at large distances and with high efficiency
- Communication with Energy Harvesting Radios
  - Intermittent and random energy arrivals
  - Communication becomes energy-dependent
  - Can combine information and energy transmission
  - New principles for radio and network design needed.

Distributed Control over Wireless

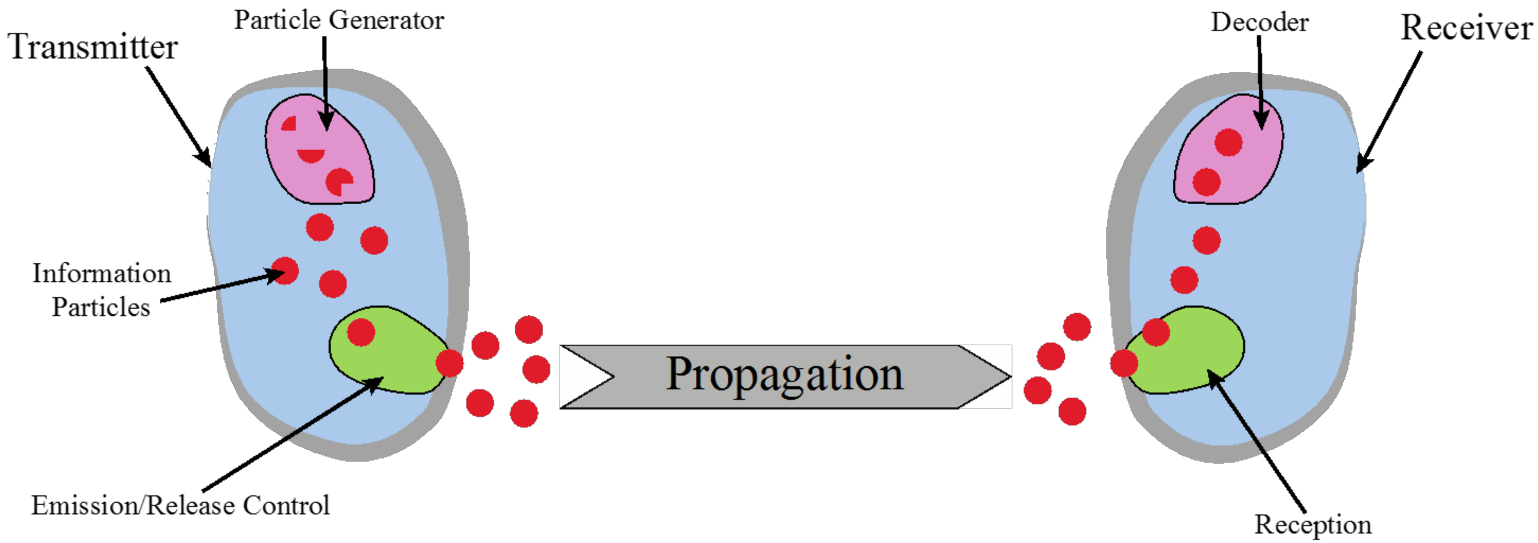


Automated Vehicles
- Cars
- Airplanes/UAVs
- Insect flyers

Interdisciplinary design approach

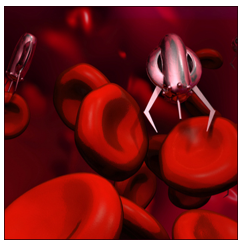
- **Control requires fast, accurate, and reliable feedback.**
- **Wireless networks introduce delay and loss**
- **Need reliable networks and robust controllers**
- Mostly open problems : *Many design challenges*

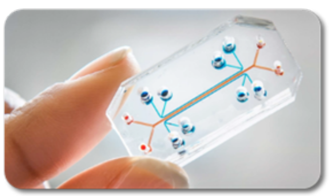
Chemical Communications

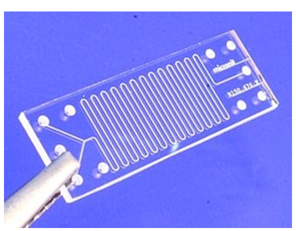


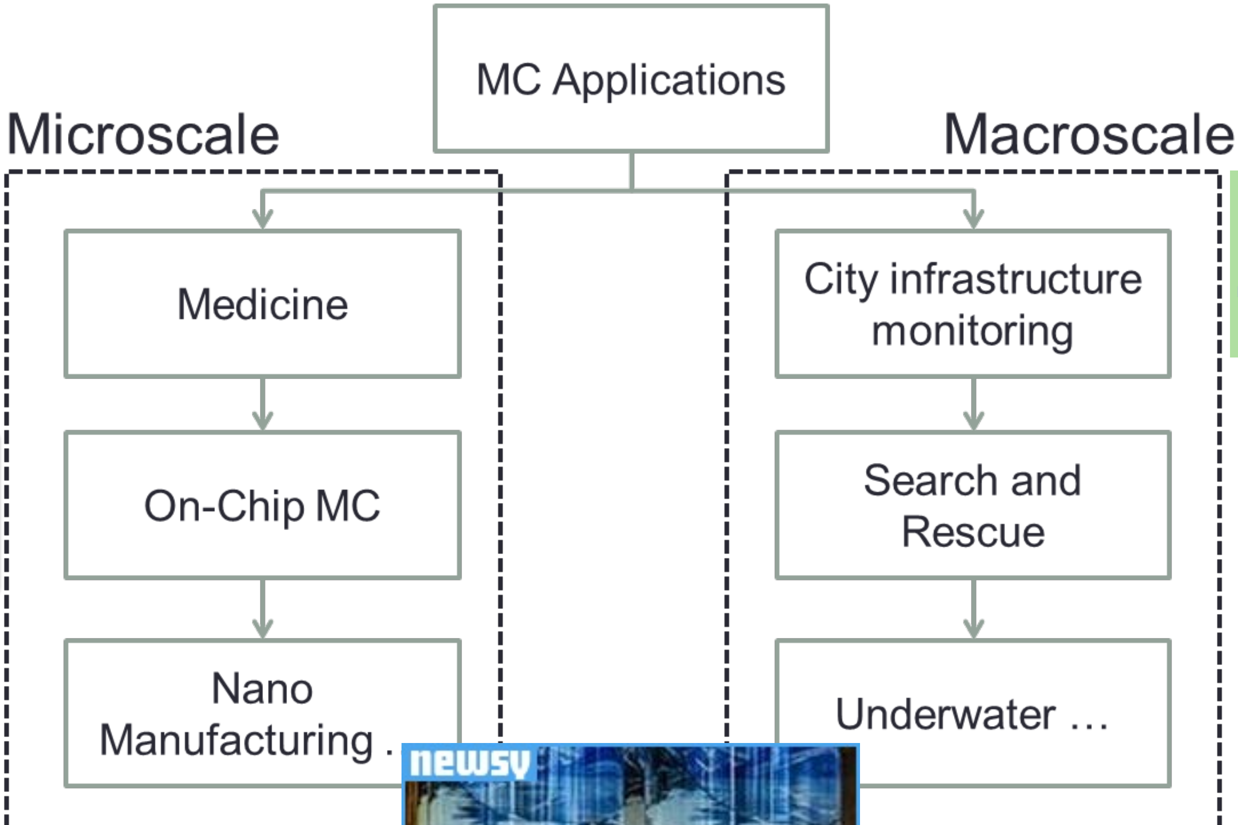
- Can be developed for both macro (>cm) and micro (<mm) scale communications
- Greenfield area of research:
  - Need new modulation schemes, channel impairment mitigation, multiple acces, etc.

Applications





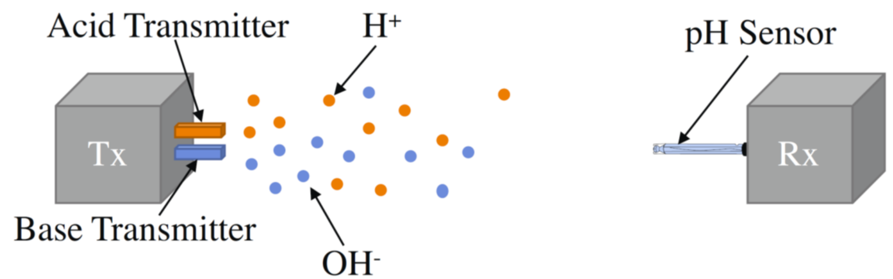




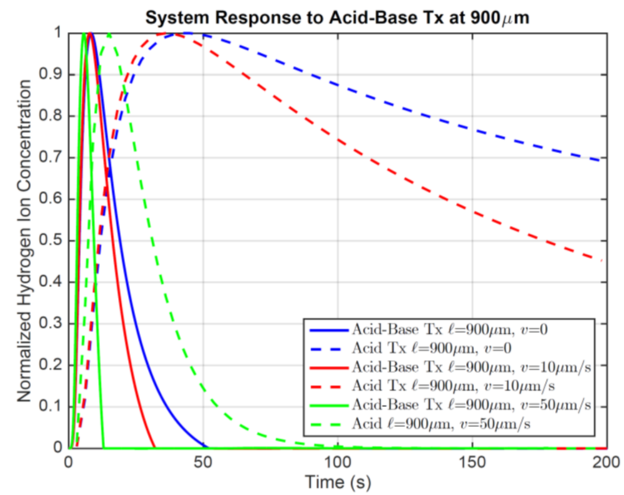
Data rate: .5 bps

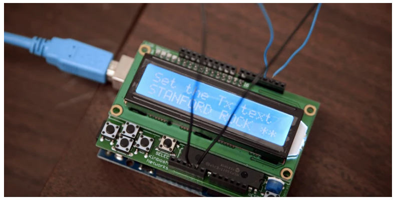
“fan-enhanced” channel

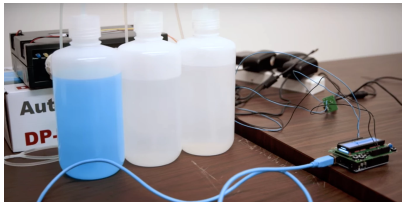
Current Work



- Slow dissipation of chemicals leads to ISI
- Can use acid/base transmission to decrease ISI
- Similar ideas can be applied for multilevel modulation and multiuser techniques
- Currently testing in our lab
  - New equalization based on machine learning
  - Increased data rate 10x



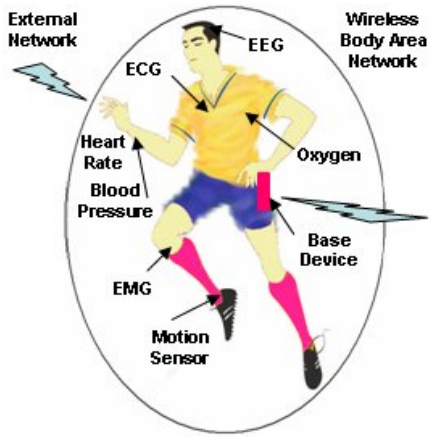




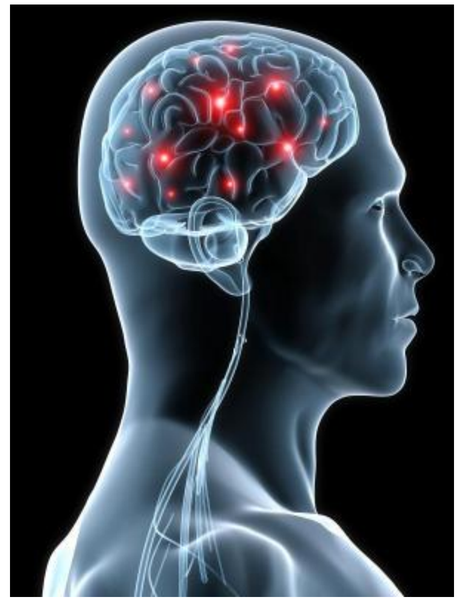
Sending text messages with windex and vinegar

Stanford Report:
November 15, 2016

Applications in Health, Biomedicine and Neuroscience



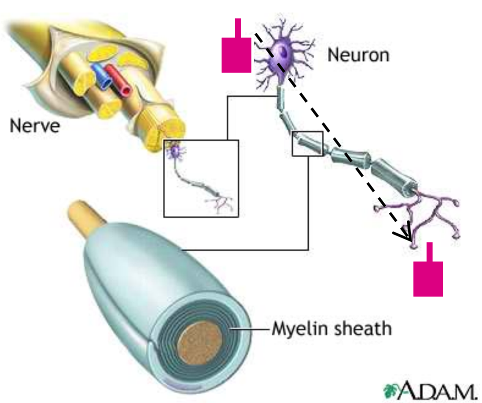
Body-Area Networks



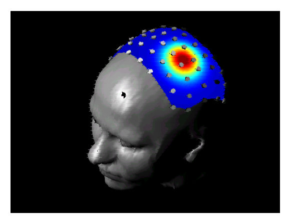
Neuroscience

-Nerve network (re)configuration
-EEG/ECoG signal processing
- Signal processing/control for deep brain stimulation
- SP/Comm applied to bioscience

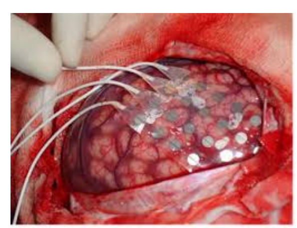
Recovery from Nerve Damage



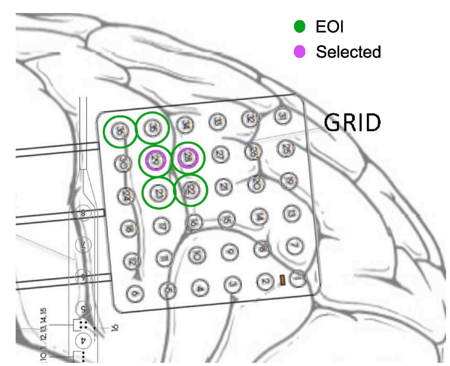
EEG



ECoG



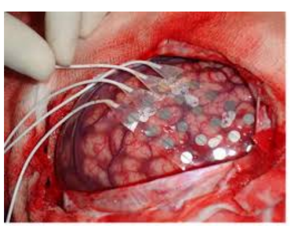
ECoG Epileptic Seizure Localization

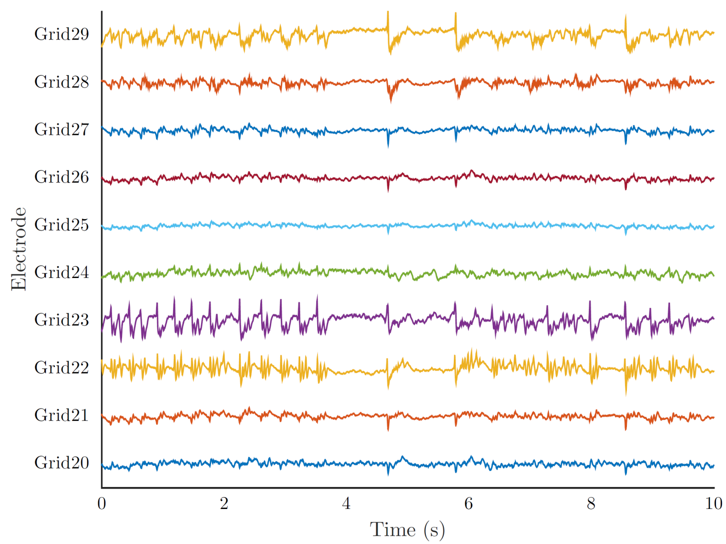


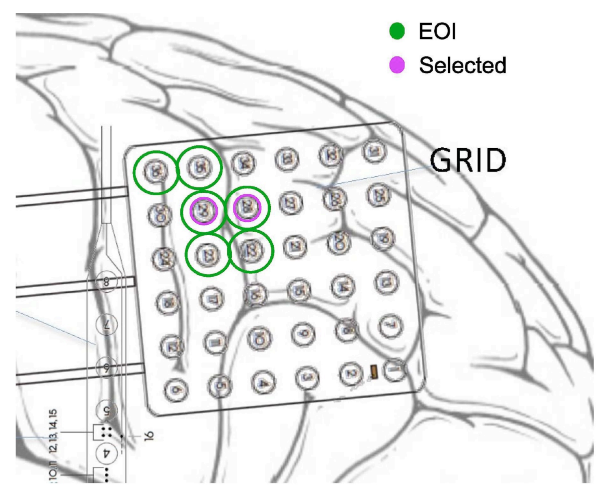
Epileptic Seizure Focal Points

- Seizure caused by an oscillating signal moving across neurons
  - When enough neurons oscillate, a seizure occurs
  - Treatment “cuts out” signal origin: errors have serious implications
- Directed mutual information spanning tree algorithm applied to ECoG measurements estimates the focal point of the seizure
- Application of our algorithm to existing data sets on 3 patients matched well with their medical records

ECoG Data







Summary

- The next wave in wireless technology is upon us
  - This technology will enable new applications that will change people's lives worldwide
- Future wireless networks must support high rates for some users and extreme energy efficiency for others
  - Small cells, mmWave massive MIMO, Software-Defined Wireless Networks, and energy-efficient design key enablers.
- Communication tools and modeling techniques may provide breakthroughs in other areas of science

The End

- Thanks!!!
- Good luck on the final and final project
- Have a great winter break

Unless you are studying for quals – if so, good luck!